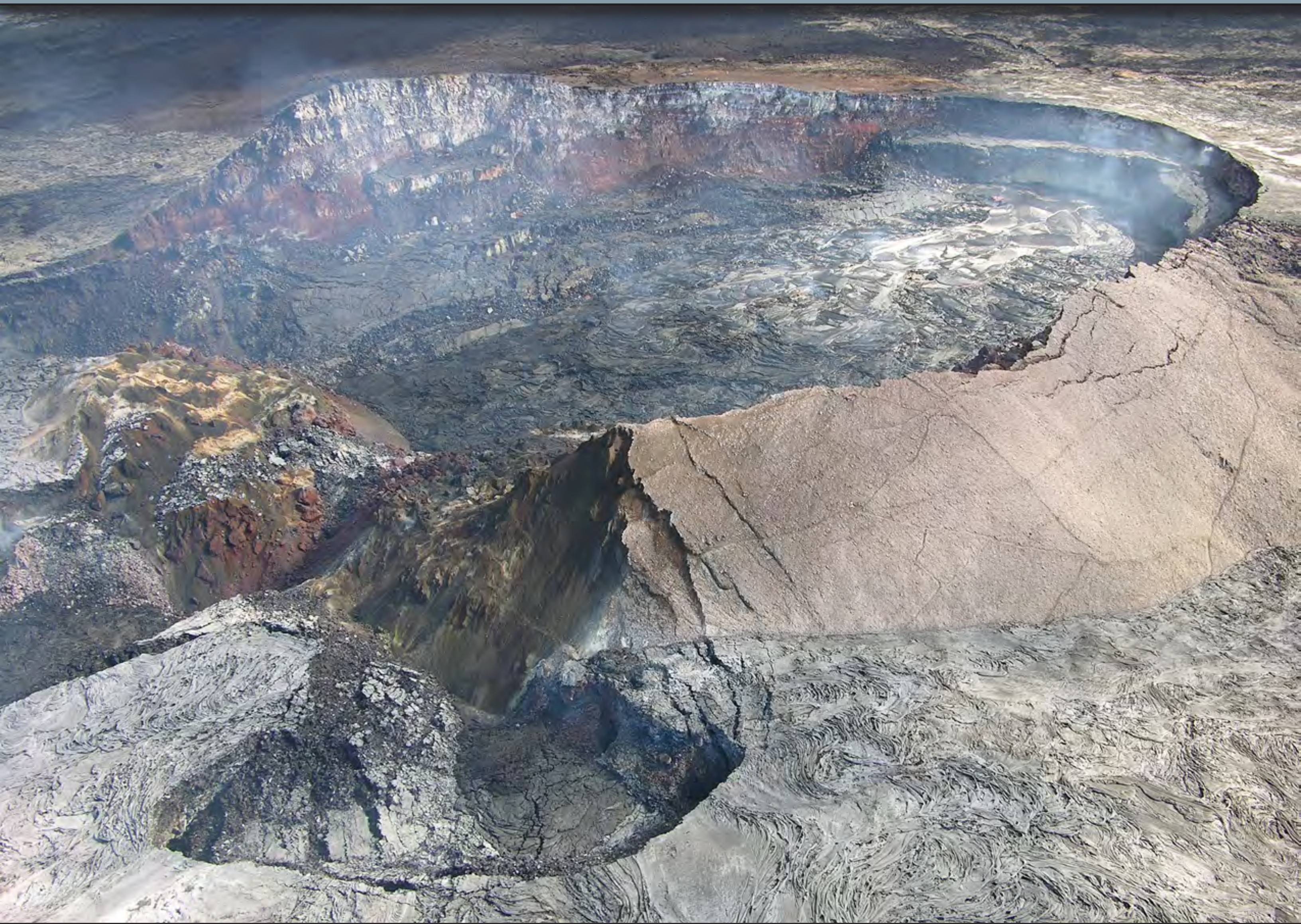
The June–July 2007 Collapse and Refilling of the Puʻu ʻŌʻō Crater, Kīlauea Volcano, Hawaiʻi



Scientific Investigations Report 2014–5124

U.S. Department of the Interior
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Cover photograph. Aerial photograph looking north at partly refilled crater at Puʻu ʻŌʻō on July 13, 2007, following its June 17–19 collapse. Photograph by Tim Orr.

The June–July 2007 Collapse and Refilling of the Puʻu ʻŌʻō Crater, Kīlauea Volcano, Hawaiʻi

By Tim R. Orr

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By Tim R. Orr

Abstract

Episode 57 of Kīlauea's long-lived east rift zone eruption was characterized by lava effusion and spattering within the crater at Pu‘u ‘Ō‘ō that lasted from July 1 to July 20, 2007. This eruptive episode represented a resumption of activity following a 12-day eruptive hiatus on Kīlauea associated with the episode 56 intrusion and eruption near Kāne Nui o Hamo cone, uprift from Pu‘u ‘Ō‘ō, on June 17–19, 2007. The withdrawal of magma from beneath Pu‘u ‘Ō‘ō led to the collapse of Pu‘u ‘Ō‘ō's crater floor, forming a concave depression ~85 m deep. After the hiatus, episode 57 lava began to erupt from two vents within Pu‘u ‘Ō‘ō, quickly constructing a lava lake and filling the crater to within 5 m of the precollapse lava level (25 m of the pre-collapse crater floor). Starting July 8, effusion waned as the crater floor began to rise. As uplift progressed, new vents opened along a circumferential fracture that accommodated the displacement. The bulk volume of filling within the Pu‘u ‘Ō‘ō crater and flank pits during episode 57, including both surficial lava accumulation and endogenous growth, is estimated at 1.3×10^6 m^3. This volume equates to a time-averaged dense rock equivalent accumulation rate of 0.6 m^3 s^{-1}, which is an order of magnitude less than the supply rate to the volcano at that time, suggesting that most of the magma entering the volcano was being stored. Eruptive activity in Pu‘u ‘Ō‘ō ended late on July 20, and the floor of the crater began to subside rapidly. Shortly afterward, early on July 21, a new fissure eruption started on the northeast flank of Pu‘u ‘Ō‘ō, marking the onset of episode 58. The June–July 2007 collapse and refilling of the Pu‘u ‘Ō‘ō crater, culminating in a new breakout outside of Pu‘u ‘Ō‘ō, illustrates the response of a long-lived eruptive center in Kīlauea's East Rift Zone to an uprift intrusion. Variations of this pattern occurred several times at Pu‘u ‘Ō‘ō before 2007 and have occurred again since. Recognition of this pattern has improved the monitoring capability of the Hawaiian Volcano Observatory and will aid in future eruption response efforts.

Introduction

Kīlauea Volcano's long-lived Pu‘u ‘Ō‘ō eruption, which began in 1983 (fig. 1; Wolfe and others, 1987; Wolfe and others, 1988; Heliker and Mattox, 2003), changed dramatically in mid-2007. An uprift intrusion and eruption on June 17–19, 2007 (episode 56; Poland and others, 2008; Montgomery-Brown and others, 2010) disrupted 10 years of nearly continuous lava effusion from vents on the southwest flank of the Pu‘u ‘Ō‘ō cone. In response, the floor of the Pu‘u ‘Ō‘ō crater dropped dramatically over a period of 3 days, and the eruption paused for 12 days.

Eruptive activity returned to Pu‘u ‘Ō‘ō late on July 1 (episode 57), and lava, erupting from two vents on the crater floor, was sighted on July 2. A lava lake developed on the floor of the Pu‘u ‘Ō‘ō crater over the next several days as the crater began to refill. By July 8, the crater floor began to lift in a somewhat piston-like fashion and, eventually, uplift superseded refilling. As uplift progressed and refilling waned, new vents opened along the circumferential fractures bounding the Pu‘u ‘Ō‘ō crater. Lava from these vents began to fill the West Gap and Puka Nui pits—collapse pits on the west flank of the Pu‘u ‘Ō‘ō cone positioned at a higher elevation than the crater floor. Just before midnight on July 20, vent activity at Pu‘u ‘Ō‘ō ceased, and the floor of the crater began to subside rapidly. Minutes later—shortly after midnight—a new fissure eruption began on the east flank of Pu‘u ‘Ō‘ō. This marked the onset of episode 58, a new phase in the Pu‘u ‘Ō‘ō eruption that continued until March 2011. Figure 2 shows a timeline that highlights the main eruptive events that occurred during the June to July 2007 interval.

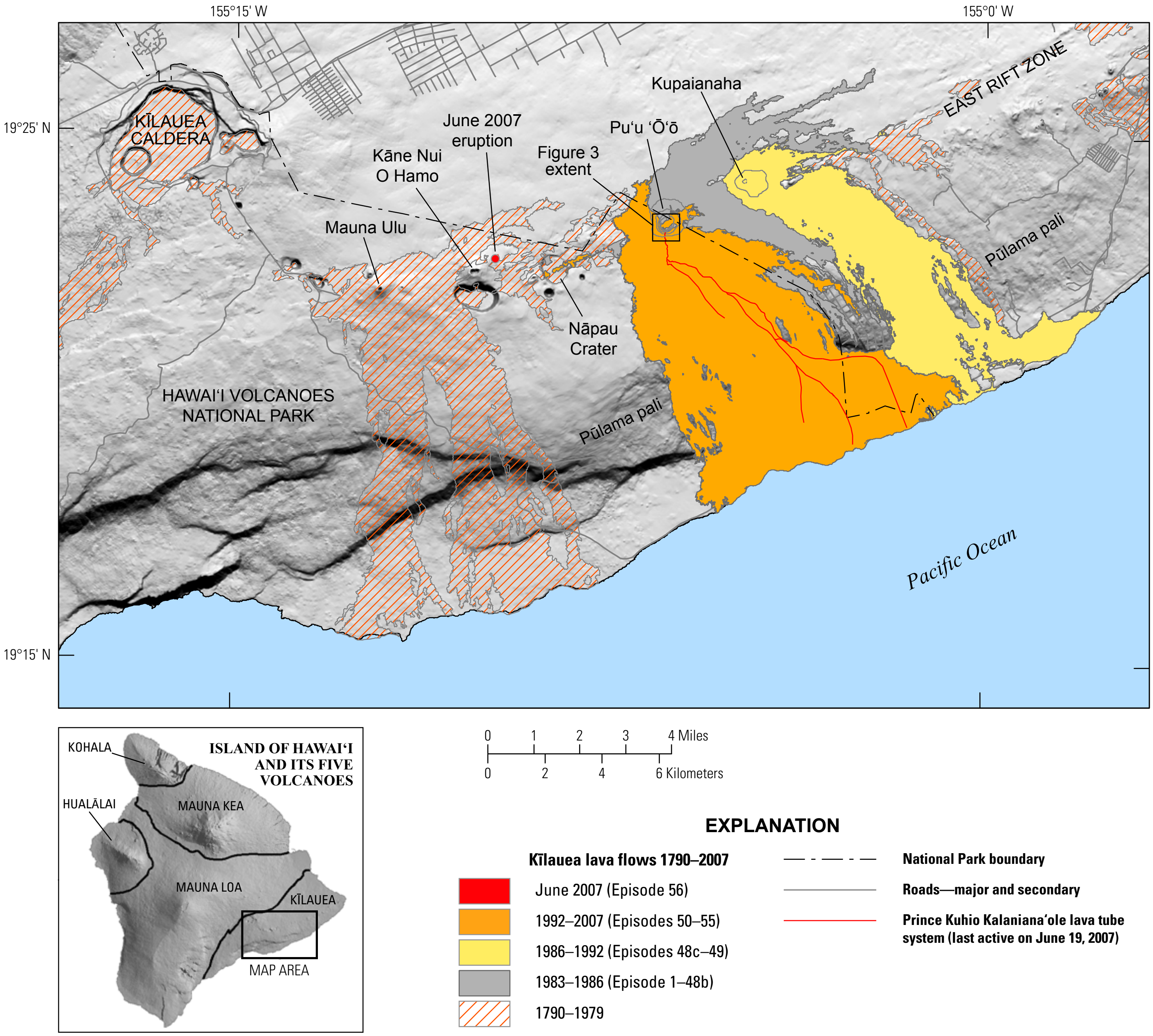

Figure 1. Map showing Kīlauea Caldera, Kīlauea’s east rift zone, historical lava flows from 1790 through 1979, and lava flows from the Pu‘u ‘Ō‘ō eruption through June 2007.

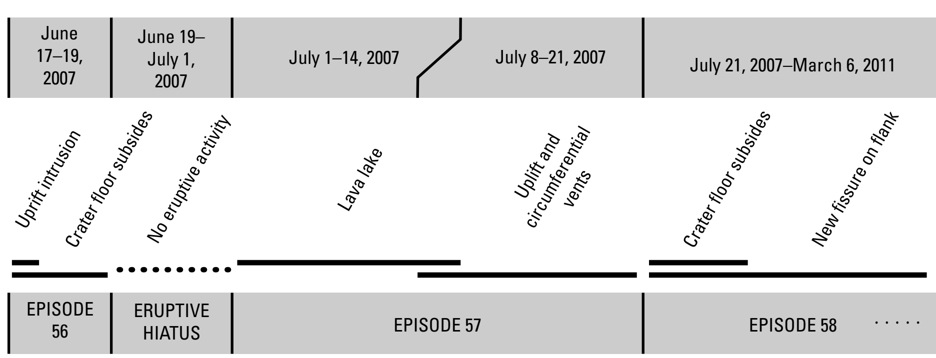

Figure 2. Timeline for episodes 56–58, with emphasis on the main eruptive events of June–July 2007. Episode 58 continued beyond this timeline, to March 5, 2011.

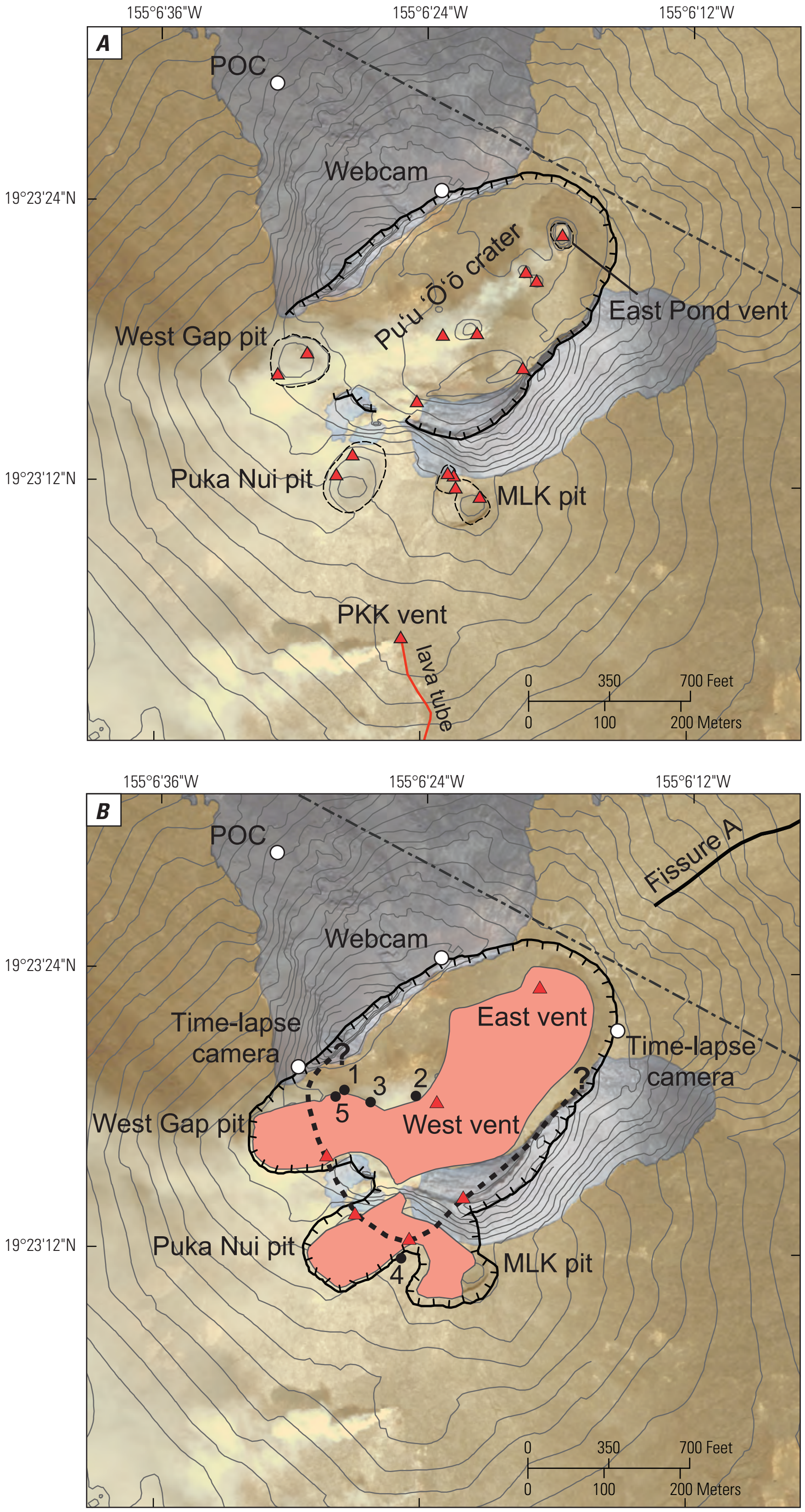

Figure 3. Map of Pu'u 'Ō'ō showing crater, flank pits, active vents (red triangles), active lava tube, and monitoring equipment (white circles). POC, tiltmeter; PKK, Prince Kūhiō Kalaniana'ole; MLK, Martin Luther King; crater rim (hachured black line); flows erupted 1992–2007 (brown); exposed Pu'u 'Ō'ō cone constructed 1983–1986 (gray). *A*, Configuration of Pu'u 'Ō'ō in early 2007 before the June 17–19 intrusion. Rim buried on west and southwest side of cone by overflows from crater before 2007. *B*, Configuration of Pu'u 'Ō'ō on July 21, 2007, after episode 57 ended. Episode 57 flows (pink); crater rim (hachured black line) connected to flank pits by collapse of septa between pits and crater on June 17–19. Approximate trace of fault accommodating uplift (dashed black line). Question marks indicate uncertainty in continuation of fracture. Lava samples (black circles) include 1 = KE57-2647F; 2 = KE57-2649F; 3 = KE57-2650F; 4 = KE57-2651S; 5 = KE57-2652F. Also shown is southwest end of fissure A of episode 58 eruption.

I report here on the transitional interval between the June 17–19, 2007, uprift intrusion and eruption (episode 56) and the July 21, 2007 to March 5, 2011, downrift eruption (episode 58). This brief, but interesting, period includes the collapse of the Puʻu ʻŌʻō crater floor following the June 17–19 event, the partial refilling of Puʻu ʻŌʻō's crater as magma returned to and repressurized the shallow magma chamber beneath Puʻu ʻŌʻō (episode 57), and the second collapse of the Puʻu ʻŌʻō crater floor, that accompanied the onset of episode 58. This sequence of events—uprift intrusion, followed by crater collapse and refilling, culminating in new breakouts from the flank of the cone—is a pattern that has been seen in three instances at Puʻu ʻŌʻō prior to the June–July 2007 sequence discussed here, and in one instance since then. Recognition of this pattern provides important guidance for responding to future intrusions at Puʻu ʻŌʻō.

Data Collection

Occasional ground observations and helicopter flights provided only brief and intermittent glimpses of dramatic changes within Puʻu ʻŌʻō during episode 57. Gaps in field observations occurred July 8–11 and July 14–18. The entire interval was monitored by a telemetered, near real-time web-based camera (webcam) and strategically positioned digital time-lapse cameras. A continuous digital-image record, as corroborated by direct field observations, documents progressive and sudden changes in eruptive conditions within the crater that can be correlated with real-time shallow deformation near Puʻu ʻŌʻō.

The webcam, of the type described by Hoblitt and others (2008), was positioned on the north rim of the Puʻu ʻŌʻō crater (fig. 3) in a long-term deployment that spanned the study period. The Puʻu ʻŌʻō webcam acquired a series of three overlapping images spanning the length of the crater with a repeat interval of 1 minute. Image pixel resolution was 640×480. Time-lapse cameras, of the type described by Orr and Hoblitt (2008), were deployed on the east and northwest rims of Puʻu ʻŌʻō (fig. 3). These cameras required manual exchange of camera memory cards to retrieve data. The eastern camera photographed the eastern part of the crater, including the East vent, with an acquisition interval of 1 minute. Operation of this camera was sporadic due to malfunctions, and image acquisition was limited to parts of June 18–19, June 21, June 25–27, July 5, and July 13. Image pixel resolution was set at 640×480. The northwestern camera captured images of the western part of the crater, including a partial view of the West vent, and was programmed with an acquisition interval of 1 minute and a pixel resolution of 640×480. This camera operated flawlessly, acquiring images for the period June 18–July 19, but subsequent images were lost when the part of the Puʻu ʻŌʻō cone on which the camera was positioned collapsed into the crater on July 21.

The webcam's angular field of view (AOV) in the vertical direction was calculated using the equation

$$\alpha = 2 \cdot \tan^{-1}\left(\frac{d}{2 \cdot f}\right) \tag{1}$$

where

- α represents the vertical AOV,
- d represents the size of the camera's optical sensor in the vertical direction (2.4 mm for a camera with 1/4-inch optical sensor), and
- f represents the focal length (4 mm; the focal length of the webcam at maximum wide-angle).

Solving for α, the camera's vertical AOV is found to be 33.4°. Each vertical image pixel, therefore, is equal to 0.07º (33.4º/480 pixels). The horizontal distance between the webcam and the steep south wall of the crater, which comprised blocks of Puʻu ʻŌʻō cone tephra, was ~245 m. At that distance, the approximate vertical size (h) of each pixel at the optical center of the webcam images was calculated at 0.3 m using the equation

$$h = D \cdot sin(\alpha) \tag{2}$$

where

- D is the horizontal distance between the webcam and the south crater wall, and
- α is the vertical AOV of each pixel as solved above.

Changes in pixel size because of the webcam view angle and crater wall slope are small and, thus, ignored.

The y-pixel value for the intersection between new lava on the floor of the crater and the south crater wall was recorded from a webcam image captured as close in time to 1200 Hawaiian Standard Time (HST) as possible (visibility dependent) each day, starting July 4, when crater visibility first improved, through July 20, the last day before the onset of episode 58. These measurements were made along a vertical axis at an x-pixel of 320±5 on the middle image of the three webcam images that compose the crater panorama. Crater uplift was recorded in the same fashion, along the same centerline, using an obvious rock face above the level of infilling as a reference point.

A Laser Atlanta Advantage laser rangefinder survey on July 13 determined the vertical distance from the crater rim to feature surfaces within the crater. The east rim of the crater had a known altitude of 860 m, allowing altitudes of these measured surfaces to be calculated. The dimensions of the crater, and of the lava surface accumulating within it, were estimated from existing crater maps. These data were used to calculate the volume of accumulated lava, as well as to constrain the rate of infilling and to track uplift of the crater floor by way of webcam images, as described above.

Deformation of the Puʻu ʻŌʻō edifice was recorded by an electronic borehole tiltmeter installed at a depth of ~3 m about 500 m north of the crater rim at an altitude of 700 m (fig. 3). Data from this tiltmeter (designated POC) were used to infer inflation and deflation of the shallow magmatic source beneath Puʻu ʻŌʻō.

Five samples of episode 57 lava, the locations of which are shown in figure 3*B*, were collected on July 19, 2007. Three samples were the glassy crust and drapery from the edge of lava flows (two were cold and erupted days earlier; one was warm and probably erupted hours earlier). One sample was air-quenched spatter collected from the ground surface near an eruptive vent. One molten sample was collected by rock hammer and quenched in water. Whole-rock major analyses for all five samples were performed at the Washington State University GeoAnalytical Laboratory in Pullman, Wash., using wavelength dispersive X-ray fluorescence techniques (Johnson and others, 1999). Microbeam quantitative analysis was performed on one sample by Carl Thornber at the U.S. Geological Survey Denver Microbeam Facility under the conditions described by Thornber and others, 2002.

Eruption Chronology

Summary of Earlier Activity (1983–2007)

The Puʻu ʻŌʻō eruption started in January 1983 as a fissure eruption in Kīlauea's east rift zone, with activity jumping from one part of the fissure system to another over the first few months as the eruption evolved (episodes 1–3; Wolfe and others, 1987; Wolfe and others, 1988). In June 1983, activity localized at a single vent, and the eruption produced a series of high lava fountains that erupted on a relatively predictable schedule (episodes 4–47). Tephra fallout and lava overflows from this vent built Puʻu ʻŌʻō, a pyroclastic cone that eventually reached an altitude of 974 m—255 m above the pre-eruption landscape (Wolfe and others, 1987; Wolfe and others, 1988; Heliker and others, 2003).

In July 1986, the conduit beneath Puʻu ʻŌʻō ruptured, and the eruption shifted 3 km downrift to form the Kupaianaha lava shield (episode 48). This marked a change in eruptive style from episodic lava fountaining to nearly continuous effusion. Over the next 5.5 years, a broad, tube-fed pāhoehoe flow field, spanning the distance from the vent to the ocean, was constructed (Mattox and others, 1993; Hon and others, 1994). During this period, the top of the Puʻu ʻŌʻō cone progressively collapsed, forming a crater that often contained a small lava lake (Heliker and others, 1998; Heliker and others, 2003).

Lava effusion from Kupanaiaha began to decline in mid-1990 (Kauahikaua and others, 1996), and activity at Puʻu ʻŌʻō began to increase commensurately, presumably as the conduit between the two vent systems became increasingly more constricted (Mangan and others, 1995). The lava lake within Puʻu ʻŌʻō rose 65 m during this period and flooded the surrounding crater floor. Then, in November 1991, the lava lake within Puʻu ʻŌʻō withdrew, and the crater floor collapsed as a fissure opened between Puʻu ʻŌʻō and Kupaianaha and erupted for three weeks (episode 49; Mangan and others, 1995). The eruptive output from Kupaianaha dropped significantly during episode 49 and continued to fall afterward, culminating in the vent's death in February 1992 (Kauahikaua and others, 1996).

Ten days later, lava began to erupt from vents on the west flank of the Puʻu ʻŌʻō cone, signaling the start of a new phase in the eruption (episodes 50–53 and 55; Heliker and others, 1998; Heliker and Mattox, 2003). Over the next 15 years, the west and south flanks of Puʻu ʻŌʻō were progressively buried beneath a lava shield, and lava flowed downslope almost continuously to widen the existing tube-fed pāhoehoe flow field. The most substantial break in this period was a brief uprift intrusion and eruption in January 1997 (episode 54; Heliker and Mattox, 2003; Thornber and others, 2003) that resulted in the collapse of the Puʻu ʻŌʻō crater floor and a part of the cone wall. Episode 54 was followed by a 24-day hiatus that ended with the resumption of eruptive activity in Puʻu ʻŌʻō at the start of episode 55, which continued the pattern of activity that characterized episodes 50–53 (Heliker and others, 1998).

Relatively steady lava effusion from Puʻu ʻŌʻō's southwest flank vents, typical of prolonged episode 55 activity, continued throughout early 2007 and until the June 17 event. The floor of Puʻu ʻŌʻō crater was ~5 m below the crater's east rim, which stood at an altitude of 860 m. Several outgassing vents were present on the crater floor and within three large collapse pits (West Gap pit, Puka Nui pit, and Martin Luther King [MLK] pit) that intersected the west and southwest edges of the crater (fig. 3*A*). Most vents were topped by spatter cones, but the easternmost (East Pond vent) was a small pit with a circulating lava lake ~20 m below the pit rim, or 25 m below the east rim of the crater at an altitude of 835 m (fig. 3*A*). In addition, lava erupted from a vent on Puʻu ʻŌʻō's southwest flank where it flowed through the Prince Kūhiō Kalanianaʻole (PKK) lava tube (figs. 1 and 3*A*) to feed active surface flows and an ocean entry. The vent and lava tube names discussed here are informal names used by the Hawaiian Volcano Observatory for identification purposes.

Collapse of the Puʻu ʻŌʻō Crater Floor

The collapse of Puʻu ʻŌʻō's crater floor was preceded by an intrusion and eruption (episode 56) near the Kāne Nui o Hamo cone on the upper east rift zone of Kīlauea Volcano, Hawaiʻi (fig. 1), on June 17–19, 2007 (Poland and others, 2008). The collapse disrupted 10 years of almost continuous East Rift Zone eruption (since the onset of episode 55 in 1997). The intrusion started at 0216 HST with the onset of rapid deflation at Kīlauea's summit. Deflation at Puʻu ʻŌʻō began minutes later, signaling that the supply of magma to the middle east rift zone had been disrupted. Outwardly, however, no change was seen at Puʻu ʻŌʻō for several hours, and the view was similar to that shown in figure 4*A*. During a helicopter flight shortly after dawn (~0745 HST) on June 17, the lava surface within the East Pond vent was observed at its typical level. Also, lava continued to flow through the PKK lava tube and was feeding active surface flows and an ocean entry that appeared unchanged compared to observations from previous days.

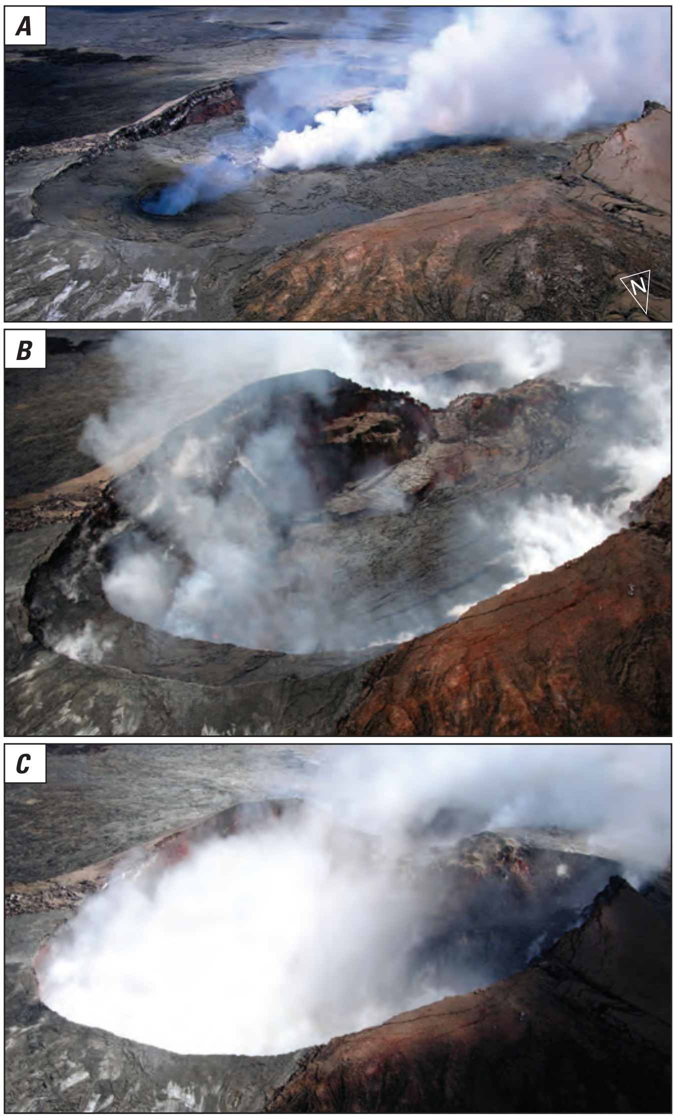

Figure 4. Time series of oblique aerial photographs of Puʻu ʻŌʻō crater. *A*, June 1, 2007, East Pond vent on east side of crater floor (left of center in photo) producing blue fume. *B*, June 18, 2007, during collapse of crater floor. *C*, June 20, 2007, after crater floor collapse had stopped.

Starting at 0935 HST, though, the webcam perched on the north rim of the Puʻu ʻŌʻō crater began to record small dust plumes caused by sporadic wall-rock collapses at pits and spatter cones on the crater floor. Visible subsidence of the crater floor began at about 1130 HST and continued throughout the day, along with more vent collapse. By the time of a second flight, at 1400 HST, the lava surface in the East Pond vent had dropped 3–5 m, and surface flows that were active downslope over the previous several days had noticeably diminished in vigor. Ground observations at Puʻu ʻŌʻō shortly afterward were enlivened by the frequent sound of rock slides from the south crater wall and wall-rock collapses in slowly enlarging pits on the crater floor. Many of the collapse events were energetic enough to be recorded by infrasound (Fee and others, 2011).

By the following morning (June 18), the crater floor of Puʻu ʻŌʻō below the north rim of the crater had dropped ~30 m (fig. 4*B*). An ~100- by 60-m lava pond (long axis oriented north–south) filled a pit on the east crater floor, where the East Pond vent had been. Adjacent to this pond, to the west, another pit had formed and hosted a small lava pond ~15 m in diameter. The lava surface within both pits was estimated to be 40–45 m below the edge of a remnant slice of crater floor attached to the east rim of the Puʻu ʻŌʻō crater. This indicated that the lava level had dropped 20–25 m since the previous morning and was at an altitude of 815–810 m.

Elsewhere, subsidence of the south crater floor had caused slumping of the south wall of the Puʻu ʻŌʻō cone. In addition, the West Gap and Puka Nui pits on the west flank of Puʻu ʻŌʻō had approximately doubled in diameter and depth, while the MLK pit increased only in depth. Aerial views into a skylight on the eastern of the two branches of the PKK lava tube showed it had been abandoned. The ocean entry, fed by the western branch of the tube system, remained active, but the steam plume had diminished substantially.

By June 19, most of the crater floor was observed to have subsided and (or) collapsed. All three pits on the west flank of the cone had grown larger and deeper, consuming parts of the adjacent walls of the Puʻu ʻŌʻō cone. At the coast, the ocean entry had dwindled to minor steaming with only sporadic drips of residual, viscous-looking lava draining into the ocean, indicating that the lava supply to the tube system had been severed. Though fume hampered views into Puʻu ʻŌʻō on June 19 and 20, brief but slightly better views on June 21 (fig. 4*C*)—after subsidence is thought to have stopped—suggested that the central part of the crater floor had subsided ~80 m and formed a concave depression, its floor composed of rubble at an altitude of ~775 m.

Steam prevented views into the crater in the days following the subsidence. Webcam images on July 4 showed a pit on the east side of the crater floor, with a depth probably similar to that of the central part of the crater, but separated from it by a septum 10–20 m higher. A part of the original crater floor, downdropped by about 15 m, remained attached to the east wall of the crater and formed a crescent-shaped shelf as wide as ~20 m. The lack of eruptive activity anywhere on Kīlauea after June 19 indicated that the volcano had entered an eruptive hiatus.

Refilling of Puʻu ʻŌʻō

Following a repose period of ~12.5 days, infrasonic energy from Puʻu ʻŌʻō resumed at ~1800 HST on July 1 (M. Garces, written commun., 2007), and weak flashes of red glow recorded by the webcam became apparent after dark at 1930 HST and continued overnight. A radiometer on the north rim of Puʻu ʻŌʻō (Harris and others, 2005), pointed toward the center of the crater, began to record elevated temperatures at 0750 HST on July 2, suggesting that lava had begun to pond at the bottom of the crater. Lava erupting from two vents (referred to hereafter as the East vent and the West vent; figs. 3*B* and 5) was sighted less than an hour later, verifying that episode 57 had begun. The two vents were positioned close to, but slightly north of, the positions of vents that had been active on the crater floor before June 17 (compare figs. 3*A* and 3*B*). Within a few days, a growing lava lake spanned much of the length and width of the crater (fig. 5*A*).

Early on July 3, the POC tiltmeter began to record an unusual saw tooth-shaped signal that slowly grew in amplitude (fig. 6*A*). The duration between peaks was ~1 hr, and the inflationary and deflationary limbs appeared to be relatively linear and symmetrical. This behavior was interspersed with, and eventually replaced by, a series of eight larger tilt excursions on July 3–6 (fig. 6; table 1) that were characterized by an abrupt and rapid inflation of 0.6–1.6 microradians and followed by an equally abrupt and rapid deflation. The inflationary and deflationary limbs were not linear and exhibited a decay pattern than created an obvious asymmetry to the shape of most events on the tilt graph. Event durations ranged from $1^h\,46^m$ to $3^h\,22^m$. Improved viewing conditions as the lava lake developed allowed the volcanic events that accompanied five of the eight large tilt excursions to be recorded, at least in part, by webcam and also, in a few cases, by the time-lapse camera deployed on the northwest rim of Puʻu ʻŌʻō.

During the four best-observed large tilt excursions (events 5–8 in fig. 6a and table 1; event 8 shown in movie 19 of Orr [2011]), the West vent stopped erupting just before the onset of rapid inflation, and the lava lake began to cool and crust over. Within minutes to a few tens of minutes, the lava lake began to drain back into the throat of the vent, leaving a funnel-shaped basin. The one observed exception was the fifth tilt excursion—the smallest of the large tilt excursions—during which the lava lake surface subsided, but lava did not obviously drain back into the vent. For all events, rapid inflation switched to rapid deflation, and, at the switch (or shortly after), lava began to erupt again from the vent and refilled the partly drained lava lake over the next several minutes. The rate of deflation decreased slowly over the next 1–2 hours, approaching, but not quite reaching, the previous tilt level. Though not every large tilt excursion was observed, it is inferred that all exhibited similar eruptive behavior. The last large tilt excursion (event 8; fig. 6) was followed by a small tilt excursion similar in shape and magnitude to the small saw tooth-shaped tilt events recorded at POC on July 3–4. Based on the webcam record, this tilt excursion was also accompanied by a drain-back event, but a commensurately smaller one which trailed the switch to deflation by several minutes. It is therefore possible that the small sawtooth-shaped tilt events described previously also recorded brief eruptive slowdowns, that may or may not have been accompanied by drain-back behavior. This inference is supported by observations made in 2010 and 2011 of a lava lake over a similarly located vent on Puʻu ʻŌʻō's crater floor. In this later case, a nearly identical small-amplitude saw tooth-shaped signal, as recorded by the POC tiltmeter, occurred repeatedly over periods of up to several days. The tilt signal corresponded to effusion slow-downs during inflation and pulses in effusion during deflation.

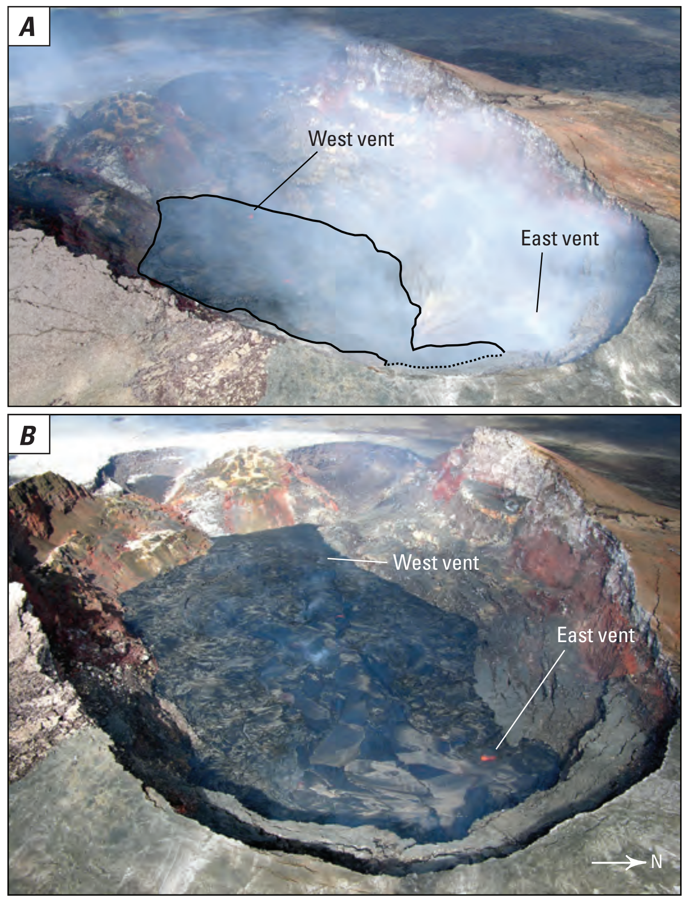

Figure 5. Oblique aerial photographs of Puʻu ʻŌʻō. *A*, July 5, 2007, lava lake outlined in black (dotted where hidden). West vent is main source of discharge with lava flowing northeast (toward lower right of photo) and pouring into pit on east side of crater. *B*, July 13, 2007, after discharge from both crater vents had waned and crater infilling had largely stopped.

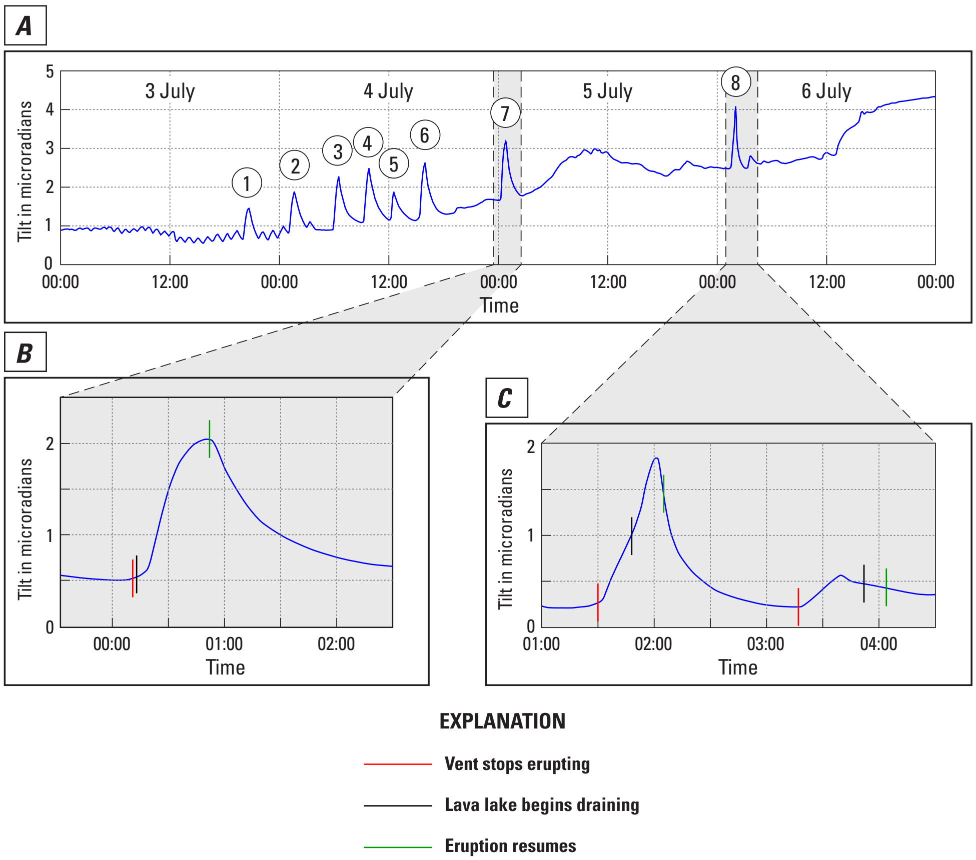

Figure 6. *A*, Graph of POC tilt-trace at azimuth of 308° for the period July 3–6, showing saw tooth-shaped tilt signals. For the large tilt excursions, cessation of eruptive activity and lava lake drain-back corresponds to periods of inflation, and resumption of eruptive activity corresponds to subsequent deflation. Numbers correlate with event numbers in table 1. *B*, Detail of tilt event #7. *C*, Detail of tilt event #8. Cessation of eruptive activity (red lines), onset of lava lake draining (black lines), and resumption of extrusive activity (green lines).

Table 1. Large sawtooth-shaped tilt events related to Pu‘u ‘Ō‘ō lava lake draining and refilling.

Event Number	Date (2007)	Duration (hr:min)	Amplitude (μr)	Observed
1	July 3	1:46	0.6	No
2	July 4	2:01	1.1	Yes (in part)
3	July 4	3:22	1.4	No
4	July 4	2:54	1.4	No
5	July 4	2:47	0.7	Yes
6	July 4	3:08	1.5	Yes
7	July 5	2:28	1.5	Yes
8	July 6	1:46	1.6	Yes

Initially, the West vent was the dominant source of lava accumulation on the crater floor, and the East vent added very little to the lava output. By July 5, lava from the West vent had filled the central part of the crater floor to a depth estimated at 10–20 m and was spilling into, and filling, the east pit (fig. 5*A*). Shortly after 1300 HST on July 6, coincident with the onset of prolonged inflation recorded by the POC tiltmeter, effusion from the East vent increased suddenly and that from the West vent stopped. Though the West vent began to erupt again by mid-morning on July 7, the East vent was the source of most of the erupting lava for the next several days (fig. 5*B*). While both vents were erupting, East vent flows crossed the crater floor toward the west, often overwhelming the West vent (see movie 20 of Orr [2011]).

As lava pooled on the crater floor, it constructed low levees, impounding a perched lava lake that stood a few meters above the surrounding crater floor. Early in the afternoon of July 12, the West vent became inactive again, and flows from the East vent were the sole source of erupting lava (see movie 21 of Orr [2011]). By July 14, the output from the East vent had also waned, with flows rarely reaching halfway across the crater floor. The West vent reactivated the same day, however, and began to erupt sporadically, feeding small flows that were confined to the west end of the crater. By July 16, cooling and subsidence of the lava lake and crater floor uplift left the levee walls standing several meters higher than the chilled surface of the lake (fig. 7). Estimates from oblique aerial photographs compared to the known dimensions of the Puʻu ʻŌʻō crater rim indicated that the crater floor, composed of new lava, had reached a maximum size of about 350- by 130-m, exclusive of the West Gap pit (fig. 3*B*). The east part of the crater floor was ~30 m below the east rim of the crater, indicating that the lava had accumulated to a depth of ~55 m.

Crater Floor Uplift

Superimposed on the infilling of the crater was the wholesale, piston-like uplift of the floor of the Puʻu ʻŌʻō crater. Starting July 8, and continuing through July 20, the Puʻu ʻŌʻō webcam recorded the slow upward movement of the crater floor, especially noticeable in slump blocks at the base of the south wall of the crater (see movie 18 of Orr (2011)). The slumped area had subsided during the collapse of the crater floor on June 17–19, indicating that it was structurally within the bounds of the crater. The onset of uplift occurred at about the peak of eruptive activity. Qualitatively, eruptive activity from vents within the crater began to wane thereafter.

The uplift was accommodated by a circumferential fault (or faults) within the Puʻu ʻŌʻō crater. The visible rim of the crater, and the rim on which the webcam viewing the uplift was located, did not move noticeably during the uplift. The webcam images suggest that the uplift was a doming of the crater floor, such that the amount of uplift was greatest over the west-central part of the crater (including the slump blocks at the base of the adjacent south wall), less on the west end of the crater, and the least at the east end of the crater. In fact, movement of the crater floor at the east end of the crater appeared to be just a slight tilting of the crater floor away from the center of uplift with no movement along a circumferential fault. No cameras had a view of the north side of the crater floor, so the presence or absence of uplift along a circumferential fault there is not known.

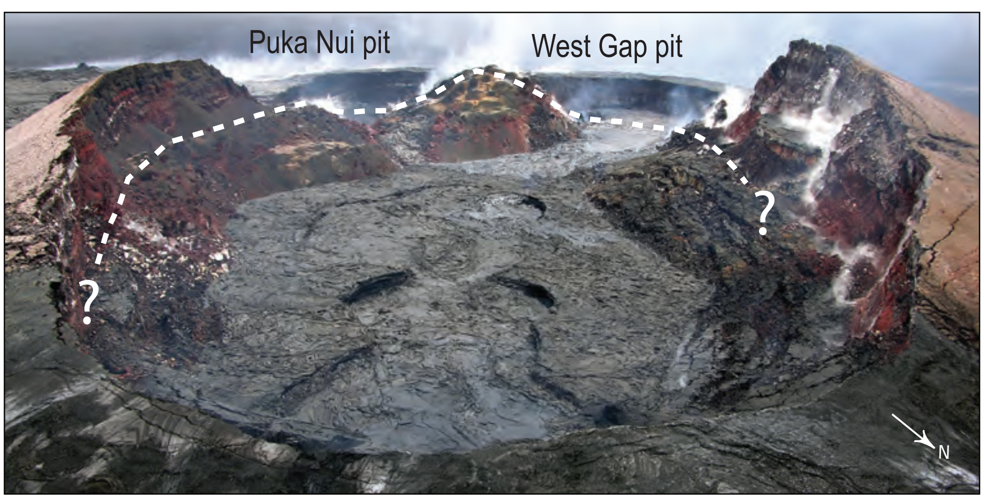

Figure 7. Oblique aerial photograph of Puʻu ʻŌʻō crater on July 16, 2007, showing exposed lava lake levees following reduced discharge from crater vents, subsidence of lava lake surface, and uplift of crater floor. Note lava erupting from vent in West Gap pit in background and flowing back into Puʻu ʻŌʻō crater. Approximate location of circumferential fault accommodating uplift (dashed white line).

Opening of Vents Along Crater-Bounding Fault

At 1500 HST on July 13, dense white fume began to emanate from rubble midway up the south wall of the West Gap pit, and lava broke the surface along a short fissure at that location at 1615 HST (fig. 8*A*). The fissure was ~20 m higher than the level of the East vent erupting simultaneously on the crater floor. Lava began to cascade down into the West Gap pit, filling it slowly over the next few days before spilling eastward into the Pu‘u ‘Ō‘ō crater. A perched lava pond ~15 m deep formed within the West Gap pit (figs. 7 and 8*B*).

White fume began to rise from the northwest edge of the Puka Nui pit (fig. 3*B*) late in the day on July 15, and, by sunrise the following day, another fume source had opened on the southeast side of the Puka Nui pit. A small pad of lava, erupted from the northwestern fuming areas some time on July 15 or 16, was observed already in place by early afternoon on July 16. The main activity within the Puka Nui pit, however, started at ~1630 HST on July 17 from the southeastern fuming area, and lava began to fill the pit slowly over the following days (fig. 9). Shortly after dawn on July 18, another source of white fume appeared on the tephra slump blocks on the south side of the crater, east of the erupting vent in the Puka Nui pit, and low-level spattering started a few hours later (fig. 9). Though the vent on the tephra slump block fed no surface flows, the vents within the Puka Nui pit eventually filled the pit and, late on July 20, began to flow northeastward into the Pu‘u ‘Ō‘ō crater, as well as southeastward into the adjacent MLK pit.

The vents that erupted in the West Gap and Puka Nui pits and on the slump block on the south edge of the Pu‘u ‘Ō‘ō crater were all located along the circumferential fracture (crater-bounding fault) that was accommodating the piston-like uplift of the crater floor. All were located at a higher elevation than the East and West vents erupting on the crater floor, and all—except perhaps the vent on the northwestern side of the Puka Nui pit—remained active through July 20.

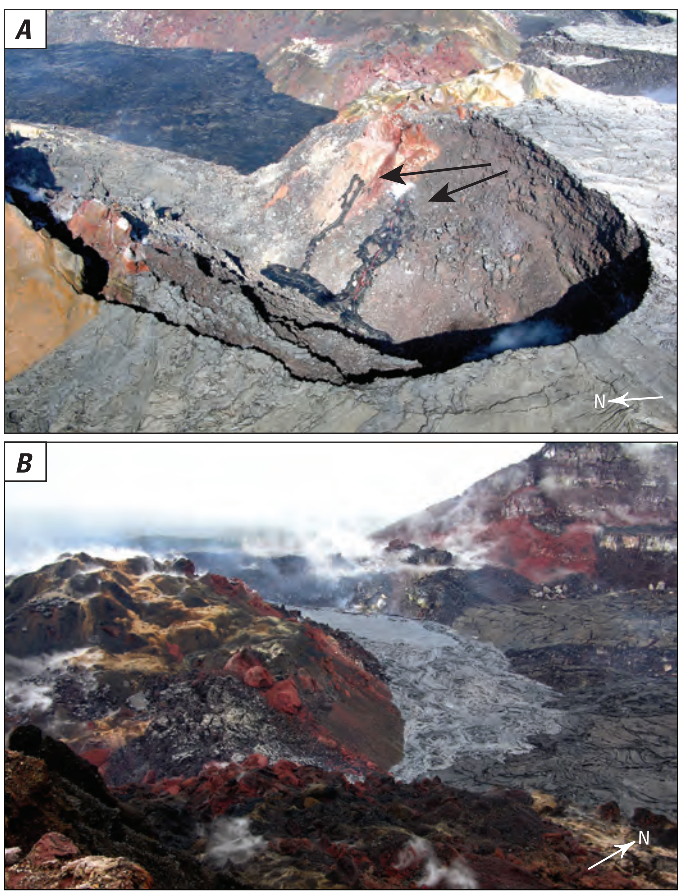

Figure 8. *A*, Oblique aerial photograph of lava erupting from short fissure on south wall of West Gap pit on July 13, 2007. Eruption onset less than two hours earlier. Lava beginning to pool at bottom of pit. Pu‘u ‘Ō‘ō’s crater at upper left of photo. Width of West Gap pit along axis extending from bottom left to top right ~125 m. *B*, Ground photograph showing lava from partly filled West Gap pit flowing back into Pu‘u ‘Ō‘ō crater on July 16, 2007. Height of crater wall at upper right ~50 m.

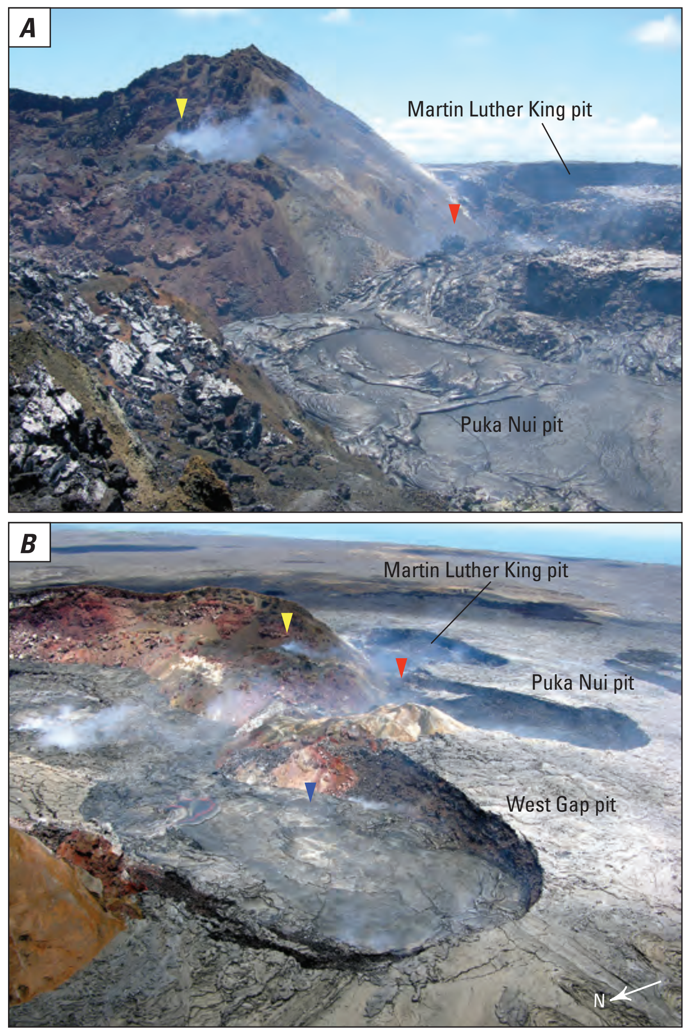

Figure 9. *A*, Ground photograph of Puka Nui pit partly filled by new lava on July 19, 2007. Source of lava (orange arrowhead); location of spattering vent in tephra slump block on south side of Pu‘u ‘Ō‘ō crater (yellow arrowhead). *B*, Oblique aerial photograph showing broader perspective of pits on southwest flank of Pu‘u ‘Ō‘ō on July 19, 2007. Vent in Puka Nui pit (orange arrowhead) and vent on tephra slump blocks (yellow arrowhead) as shown in *A* above; vent in West Gap pit (blue arrowhead).

Resumption of Crater Vent Effusion

The East vent within Puʻu ʻŌʻō erupted flows sporadically through July 20, but all were small and confined to the area immediately surrounding the vent. The West vent was also a source of small, sporadic flows during this period, but during mid-afternoon on July 18, lava began to erupt vigorously from the West vent. Though not matching the level of activity observed earlier in July, flows began to pond on the west side of the crater, largely confined by the levees from the earlier-formed lava lake. Activity increased over the following few days and, by late in the day on July 20, West vent flows had reached nearly to the east end of the crater, where they occasionally converged with small flows fed from the East vent.

Onset of the July 21, 2007, Fissure Eruption

Eruptive activity within Puʻu ʻŌʻō and from the vents along the crater-bounding fault stopped at ~2250 HST on July 20, coincident with the abrupt onset of rapid deflationary tilt toward the southeast as recorded by the POC tiltmeter. Though the supply had been severed, lava flows continued to advance across the crater floor until ~2315 HST. At 2355 HST, the floor of the Puʻu ʻŌʻō crater began to subside rapidly. Minutes later—shortly after midnight on July 21—lava began to erupt from a new fissure high on the northeast flank of the Puʻu ʻŌʻō cone (fig. 3*B*). The first acoustic signal from the direction of Puʻu ʻŌʻō's east flank was detected at 0006 HST and a higher amplitude signal appeared at 0013 HST (Fee and others, 2011), suggesting an eruptive onset at one of these two times. Definitive glow was first detected beyond the east rim of Puʻu ʻŌʻō by webcam at 0039 HST. Over the next several hours, a series of four left- and right-stepping, en echelon fissure segments propagated ~1.5 km downrift. This signaled the start of episode 58 and a new phase within the long-lived Puʻu ʻŌʻō eruption (Poland and others, 2008).

Puʻu ʻŌʻō underwent a prolonged, but rather dramatic, response to the episode 58 eruption. By the following day, the floor of the crater had sagged ~20 m, and a small collapse pit had formed at the site of the West vent. Thick fume obscured views of the East vent and the east end of the crater. The center of the West Gap pit had dropped ~20 m, and a part of the northwest rim of Puʻu ʻŌʻō, on the north side of the West Gap pit, had collapsed, destroying the time-lapse camera located at that spot. Pre-existing cracks on the north rim of Puʻu ʻŌʻō widened, and new cracks formed.

Despite the presence of opaque fume that obscured most views into the crater, rare glimpses indicated that the crater floor continued to collapse and deepen over the following months, possibly in response to the slow draining of magma from beneath Puʻu ʻŌʻō as the episode 58 eruption evolved. Many collapses were recorded by nearby seismometers during this period, each accompanied by small, positive tilt offsets recorded on the POC tiltmeter. Some collapses deposited mud onto the window of the webcam enclosure on the north rim of the crater. The eventual result of crater subsidence was a bowl-shaped depression floored by rubble, its low point 95–100 m below the east rim of the crater.

Results and Discussion

Crater Floor Collapse

The shape of the Puʻu ʻŌʻō crater floor after the collapse on June 17–19 was complex, but in simplest form can be approximated as a half-ellipsoid. A collapse volume (V_c) can therefore be calculated from

$$V_c = \frac{\pi\, l\, w\, h}{6} \tag{3}$$

where

l	is the crater length,
w	is the crater width, and
h	is the collapse depth.

Using crater dimensions of 400- by 280-m (pre-collapse dimensions), and a collapse depth of 80 m, the derived volume of the crater collapse is 4.2×10^6 m^3. This is similar to the volume-loss approximation of 3.65×10^6 m^3 of lava calculated by Montgomery-Brown and others (2010) based on the length of time required for lava to reappear at Puʻu ʻŌʻō. Experimental work on crater-collapse mechanisms by Roche and others (2001) suggests that, following collapse, Puʻu ʻŌʻō's crater was probably a column of brecciated material occupying a volume greater than that of the same material preceding the collapse. Thus, the crater collapse volume calculated here may represent a minimum value.

Crater Infilling and Uplift

Equation 3 above can also be used to calculate a bulk volume of filling within Puʻu ʻŌʻō. Using the maximum lava lake dimensions of 350×130 m and a depth of 55 m, the bulk volume erupted in Puʻu ʻŌʻō was ~1.3×10^6 m^3 by July 13, after which crater activity began to wane significantly. Likewise, assuming half-ellipsoids for the shape of the West Gap and Puka Nui pits, approximate bulk volumes can also be calculated for lava erupted from vents around the periphery of the crater. By July 20, lava had accumulated in the West Gap pit to a depth of ~15 m with a surface area of ~100- by 80-m and in the Puka Nui pit to a depth of ~15 m with a surface area of ~120- by 70-m. These dimensions yield volumes of ~0.06×10^6 m^3 and ~0.07×10^6 m^3, respectively.

The total bulk volume of lava accumulated within the Puʻu ʻŌʻō crater, the West Gap pit, and the Puka Nui pit from July 1 to July 20, including both surficial lava flows and endogenous growth, was ~1.4×10^6 m^3 (the relatively small volume of lava erupted within Puʻu ʻŌʻō from July 18 to July 20 is disregarded). The resulting bulk discharge rate, averaged over the 20 days, is 0.8×10^6 m^3. Correcting for vesicle volume, using a modest void fraction of 25 percent (Wolfe and others, 1987), gives a dense rock equivalent discharge rate of 0.6 m^3 s^{-1}, which is about an order of magnitude less than the supply rate of magma to the volcano during the same period (Poland and others, 2012). This disparity suggests that most of the magma supplied to the volcano went into refilling and (or) repressurization of magma storage at the summit and along the East Rift Zone between the summit and Puʻu ʻŌʻō.

Webcam images provided a way to track changes in both lava level and uplift within the Puʻu ʻŌʻō crater, as shown in figure 10. Because the measured lava level reflected the cumulative effect of both filling and uplift, actual filling was isolated by subtracting the amount of uplift. The result (blue line; fig. 10) shows—at least along the centerline of the images used to track changes—essentially no filling after July 9 and essentially no uplift before July 9. In other words, filling stopped once uplift began. The POC tilt record shows a slowly accelerating rate of inflation starting about July 3. On July 11, though, the tilt flattens, showing no net tilt gain or loss until about July 13, when slow inflation starts again. After July 13, however, shortly after the rate of uplift had increased, the tilt leveled out and showed no significant gain or loss until late on July 20, just before the onset of the July 21 fissure eruption. The absence of inflation while the Puʻu ʻŌʻō crater floor was uplifting suggests that this uplift was driven at a shallow level within the Puʻu ʻŌʻō edifice, and (or) that pressurization of the shallow magma body beneath Puʻu ʻŌʻō was almost completely accommodated by crater floor uplift.

The data show ~16 m of filling from July 4 to July 9. This brackets the minimum amount of crater filling and implies that 34 m (based on original estimate of maximum infilling of 50 m) of lava accumulated from July 2 (when filling probably started) to July 4. The filling curve for 34 m is shown as the dashed blue line in figure 10. Based on the webcam images, the crater floor was lifted ~10 m between July 9 and July 20 (red line; fig. 10).

Onset of Episode 58

The western tip of the episode 58 eruptive fissure system was located ~110 m northeast of Puʻu ʻŌʻō's east crater rim (fig. 3*B*). The tip of the fissure was 24 m lower than the crater rim and ~6 m higher than the level of lava on the crater floor. Cracks that defined the westward extension of the fissure continued westward, but did not intersect the crater rim. In addition, the tip of the fissure was bounded by a zone of circumferential fractures. Views of Puʻu ʻŌʻō's east crater wall in the months following the onset of episode 58, when the crater floor had reached a depth estimated at 95–100 m below the crater's east rim, showed no evidence of a lateral connection between the crater and the episode 58 fissure.

These observations show that the episode 58 fissure was not fed directly from a lateral breach of the cone by lava that had accumulated within the Puʻu ʻŌʻō crater. Instead, magma that fed the episode 58 fissures probably originated directly from the shallow conduit, bypassing the Puʻu ʻŌʻō crater above. The subsequent depressurization (eruption) resulted in crater floor subsidence and perhaps some recycling of molten lava still present beneath the crusted surface of the lava lake on the crater floor.

Eruption Petrology

Starting in April 2001, the olivine-phyric magma that had been erupting at Puʻu ʻŌʻō changed to a mixture of olivine-only magma and a cooler magma containing clinopyroxene phenocrysts and glomerocrysts (± olivine ± plagioclase). This change is thought to be derived from the mixing of hotter and cooler components within the magmatic system (Thornber

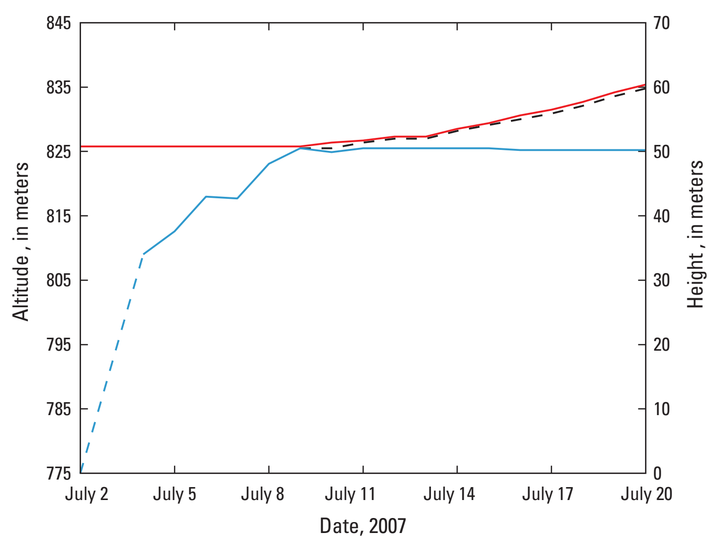

Figure 10. Graph showing altitude and height of crater floor from filling (blue) and crater uplift (red) in meters, for the period July 2–20, 2007. Presumed July 2 to July 4 filling path (dashed blue line); altitude of lava surface with uplift not subtracted out, that is, the actual altitude of the crater floor (dashed black line).

and others, 2007). Glass temperature and bulk MgO decreased slowly and finally stabilized at ~1,146º C and ~7.1 weight percent, and remained stable through the end of episode 55 in June 2007.

Episode 56, however, erupted a hotter (1,160º C) and more Mg-rich (8.7 weight percent MgO) olivine-only basalt, probably representing the primitive end-member for the mixed magma erupted since 2001 (Thornber and others, 2007). When the eruption resumed at Puʻu ʻŌʻō with the start of episode 57, a cooler (1,143º C) low-MgO (~7.3 weight percent), olivine- and clinopyroxene-phyric lava (table 2) erupted once again, and this hybrid magma continued to erupt during episode 58 (Thornber and others, 2007). This suggests that the magmatic system was not significantly disrupted by the episode 56 eruption, and that the presumed hybridization of hotter and cooler magmatic components likely occurs along the east rift zone enroute to Puʻu ʻŌʻō, possibly beneath Makaopuhi Crater where a zone of magma storage may exist (Fiske and Kinoshita, 1969; Swanson and others, 1976).

Trends in Intrusive and Eruptive Activity

Most published overviews of the prolonged Puʻu ʻŌʻō eruption, including the one here, tend to lump three decades of eruptive activity into a few paragraphs. In the interest of brevity, only the most profound changes are noted. This may give the false impression that the Puʻu ʻŌʻō eruption is largely a "steady-state" eruption. In reality, the Puʻu ʻŌʻō eruption represents a continuum of changes. Relatively steady conditions, though rife with small changes, may prevail for months to at most a few years, but the magmatic system inevitably breaks down. Such large changes commonly culminate in the transition to a new eruptive vent, or a major reorganization of the lava tube system transporting lava away from the vent. With the benefit of time, trends have begun to emerge that forecast some of these profound changes.

One such trend—uprift intrusion with or without eruption, accompanied by crater floor collapse and eruptive hiatus—has repeated several times at Puʻu ʻŌʻō. Such

Table 2. Description and major element composition of episode 57 lava samples. Glass temperature for sample KE57-2647F calculated by technique of Helz and Thornber (1987). HST, Hawaiian standard time.

Sample no.:	KE57-2647F		KE57-2649F	KE57-2650F	KE57-2651S	KE57-2652F
Collection date/time:	7/19/07 11:00 HST		7/19/07 11:15 HST	7/19/07 11:20 HST	7/19/07 11:55 HST	7/19/07 12:25 HST
Description:	Warm crust from hours-old lava flow		Cold crust of lava erupted since 7/2	Cold drapery at edge of lava flow 2–3 days old	Cold spatter erupted since ~1630 on 7/17	Molten core from 15-min-old stagnant toe; water quench
Analysis:	XRF	Microprobe	XRF	XRF	XRF	XRF
SiO_2	51.16	51.31	51.15	51.16	51.2	51.26
Al_2O_3	13.71	13.39	13.67	13.73	13.68	13.82
FeO_T	11.25	11.1	11.23	11.17	11.22	11.17
MgO	7.23	6.4	7.39	7.32	7.3	7.07
CaO	11.05	10.64	11.01	11.03	11.02	11.02
Na_2O	2.34	2.32	2.31	2.33	2.33	2.36
K_2O	0.41	0.429	0.41	0.41	0.41	0.42
TiO_2	2.45	2.535	2.43	2.44	2.44	2.48
P_2O_5	0.23	0.25	0.23	0.23	0.23	0.24
MnO	0.17	0.16	0.17	0.17	0.17	0.17
Cr_2O_3	–	0.032	–	–	–	–
SO_3	–	0.02	–	–	–	–
NiO	–	0.004	–	–	–	–
TOTAL (weight percent)	100	98.56	100	100	100	100
MgO T (ºC)	–	1,142.6	–	–	–	–

sequences were initiated by the February 7, 1993, intrusion (Okubo and others, 1996; Heliker and others, 1998); the January 29, 1997, intrusion and eruption (Owen and others, 2000; Thornber and others, 2003); the September 12, 1999, intrusion (Cervelli and others, 2002); and the June 17, 2007, intrusion and eruption (Poland and others, 2008; Montgomery-Brown and others, 2010). Activity resumed within Puʻu ʻŌʻō following each of these events, and crater refilling eventually culminated in the outbreak of lava from new vents on the flank of the Puʻu ʻŌʻō cone. The sequences in 1993 and 1999 involved the reoccupation of the previously active vent and a reorganization of the tube system, while the sequences in 1997 and 2007 (the focus of this report) led to the opening of new vents.

The pattern was repeated in 2011, when an intrusion and brief fissure eruption uprift from Puʻu ʻŌʻō started on March 5 (Lundgren and others, 2013). The sequence of events that followed culminated on August 3, 2011, in a large, rapidly moving breakout on the west flank of the Puʻu ʻŌʻō cone (episode 60) and another collapse of the crater floor of Puʻu ʻŌʻō. Recognizing that the pattern of intrusion, crater collapse, and refilling could culminate in a major breakout on Puʻu ʻŌʻō allowed Hawaiian Volcano Observatory scientists to prepare a response well in advance of the August 3 event. As in July 2007, the crater floor prior to the August 2011 breakout began to bodily lift via endogenous accumulation, providing a telltale sign of the increased pressure within the Puʻu ʻŌʻō edifice. While not always present (there was no evidence of such uplift in 1993, 1997, or 1999), this uplift provides additional guidance for forecasting changes in activity in some instances.

Conclusions

In this paper, I have presented a detailed chronology of the events associated with the June–July 2007 collapse and refilling of the Puʻu ʻŌʻō crater on Kīlauea's east rift zone. Of special note was the transition from the surficial accumulation of lava to uplift of the crater floor via endogenous processes. The sequence of events in 2007 unfolded in a somewhat predictable fashion, based on Puʻu ʻŌʻō's previous response to uprift intrusions. Recognition of the pattern of east rift zone intrusion, followed by crater collapse, refilling, and breakout at Puʻu ʻŌʻō, provides guidance when preparing for future eruption crises that evolve similarly. In fact, the occurrence of another uprift intrusion and eruption (episode 59) on March 5, 2011, followed a strikingly similar pattern, with crater floor collapse, eventual refilling of the crater evolving into crater floor uplift, and culmination with the opening of a new vent (episode 60) on the west flank of Puʻu ʻŌʻō. The lessons learned from episode 57 guided the Hawaiian Volcano Observatory in responding preemptively to the August 3 breakout.

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